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# High Performance Packaging of Power Electronics:

## *Role of Thermally Engineered Materials*

M.C. Shaw

*Rockwell Science Center, Thousand Oaks, CA*

**30 May, 2001**

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14. ABSTRACT
? Advantages of new approaches must be demonstrated at the system, e.g., motor drive, level. Device Power Density (A/cm2 or W/cm2 ) System Power Density (W/m3) Lifetime Assurance of Entire System System Cost Analysis Ultimately Required

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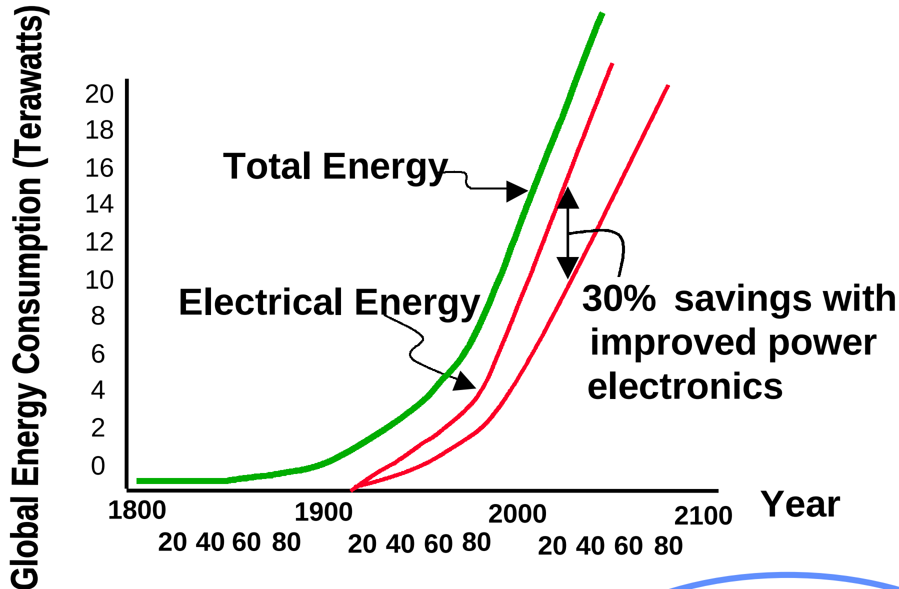
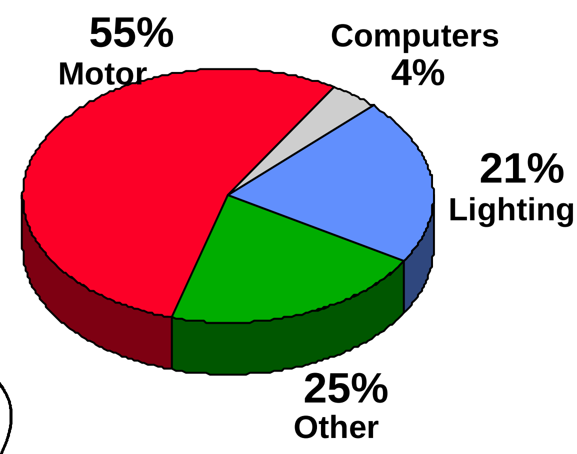
# Global Energy Consumption and Power Electronics

***(Source: NSF Center for Power Electronic Systems:*** http://www.cpes.vt.edu/]***)***




*** Output of 840 power plants**

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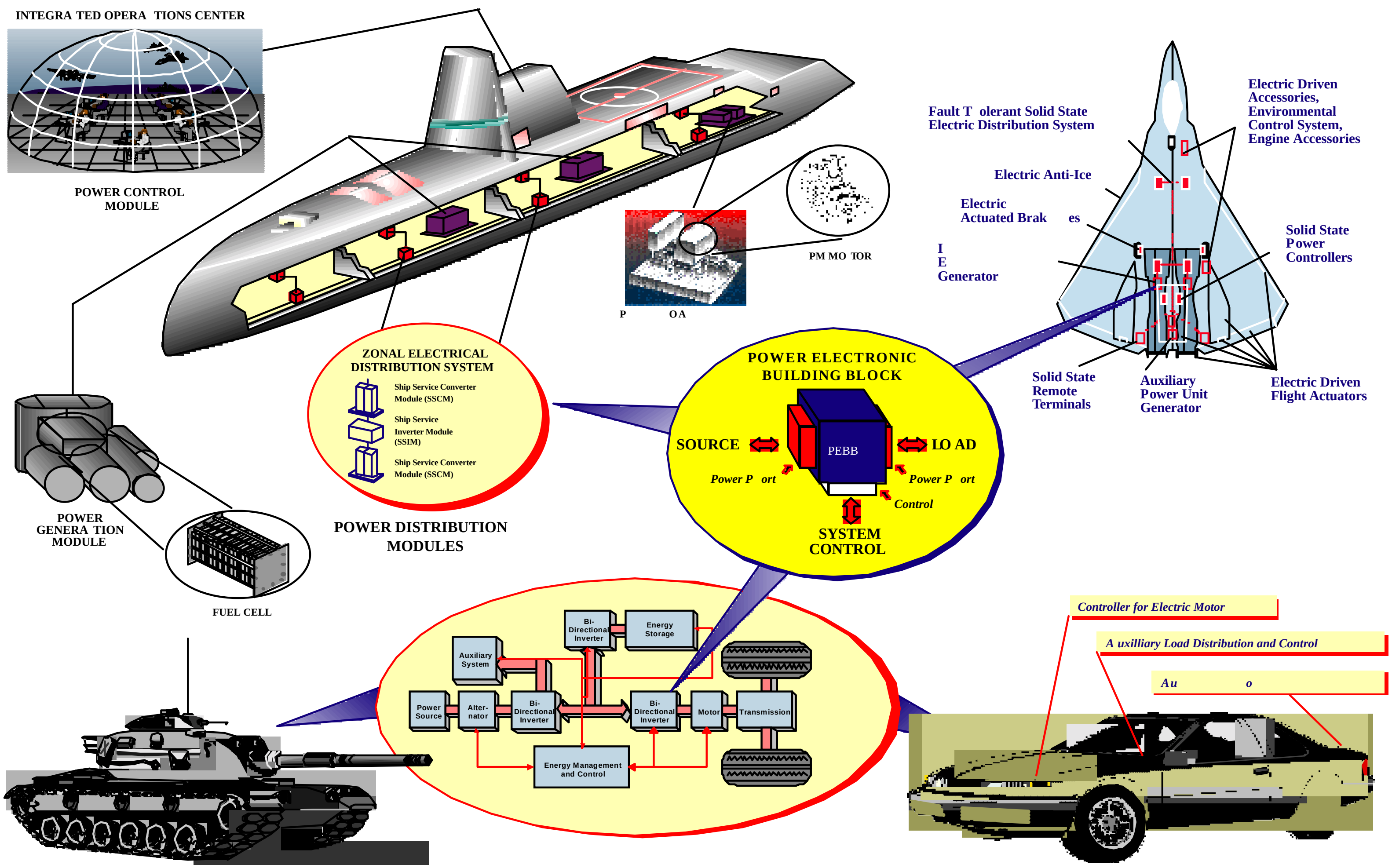
* EPRI

# Defense Power Electronics Requirements Example: PEBBs

Courtesy of G. Campisi, Office of Naval Research



# Power Electronic Systems

- **Motor Drives**

Today's Topic

- **Radar / Microwave Communications**
- **dc to dc Converters**
- **Power Supplies**
- **Electric Vehicle Drives**
- **Weapons Systems**

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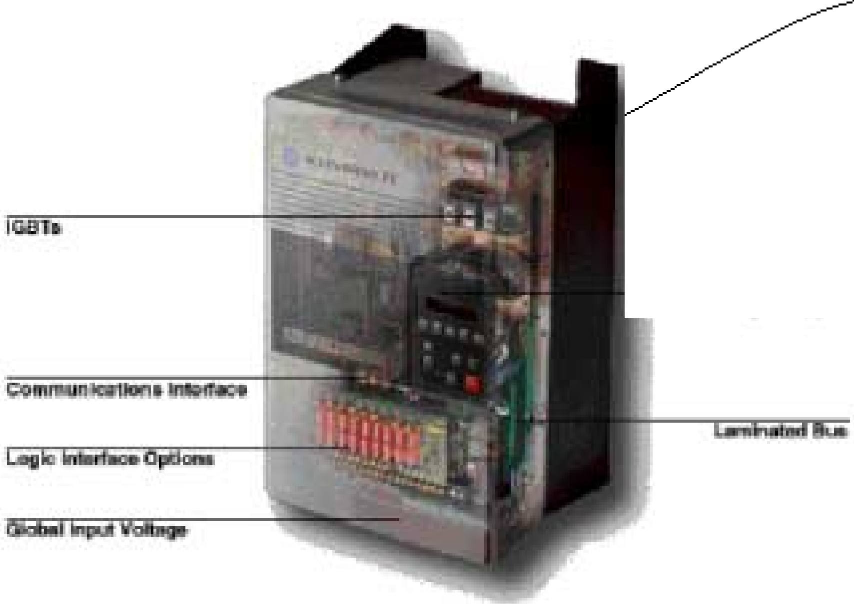
# Drive & Motor *Automation System*

**Rockwell Automation - Allen Bradley 1336 Force Drive**




***Performance Metrics:***
- ***Power Density***
- ***Cost***
- ***Reliability***

**Rockwell Automation**
**Reliance Electric AC Motor**

**Converts AC power (<u>fixed</u> frequency, voltage) to**
**AC Power (<u>variable</u> frequency, current, and voltage)**

**Enables exact control of speed (RPM) and torque of *motors***

**Motors *become controlled electromechanical energy converters*.**

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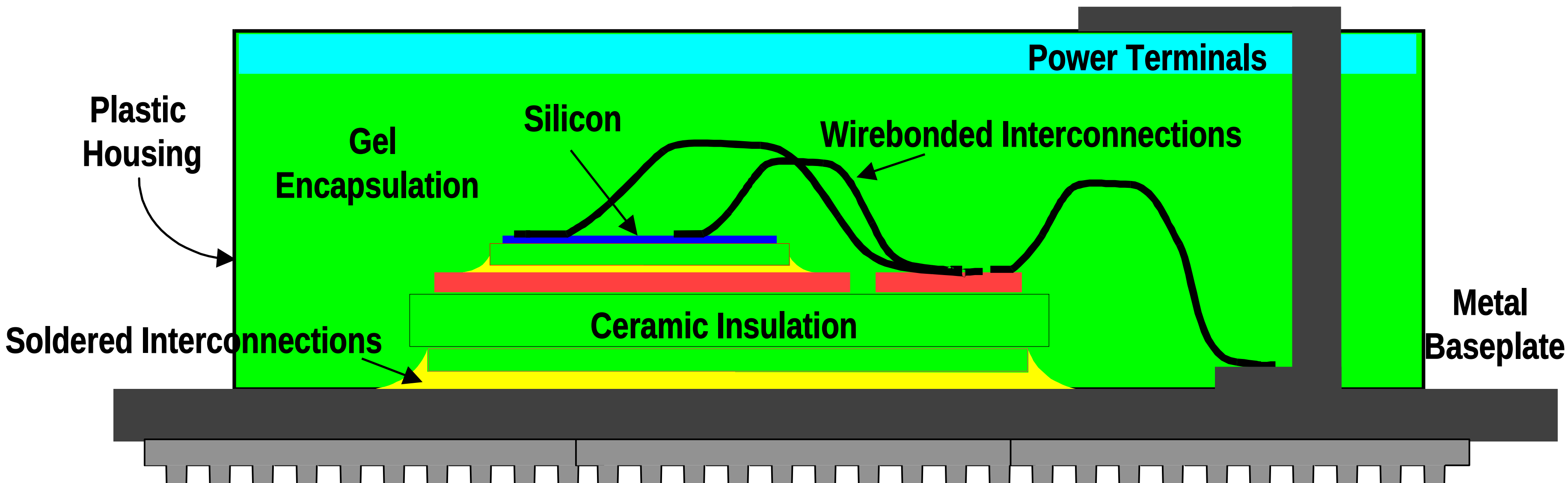
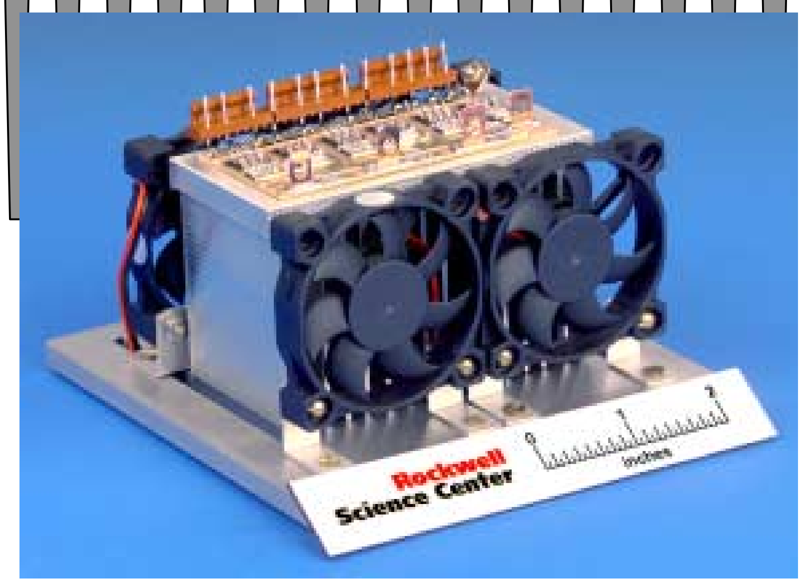
# Basic Power Packaging Elements

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# Generic Electronic Packaging Technology Hurdles

Controlled Power Density ( $W / m^3$ )

High Power Requirements from Devices
High Packaging Densities
Weight Requirements

Cost ( $ / Function )

Reliability ( MTBF )

# High-Temperature Packaging of SiC Electronics

M.C. Shaw, J.R. Waldrop, F. Zok,[1]

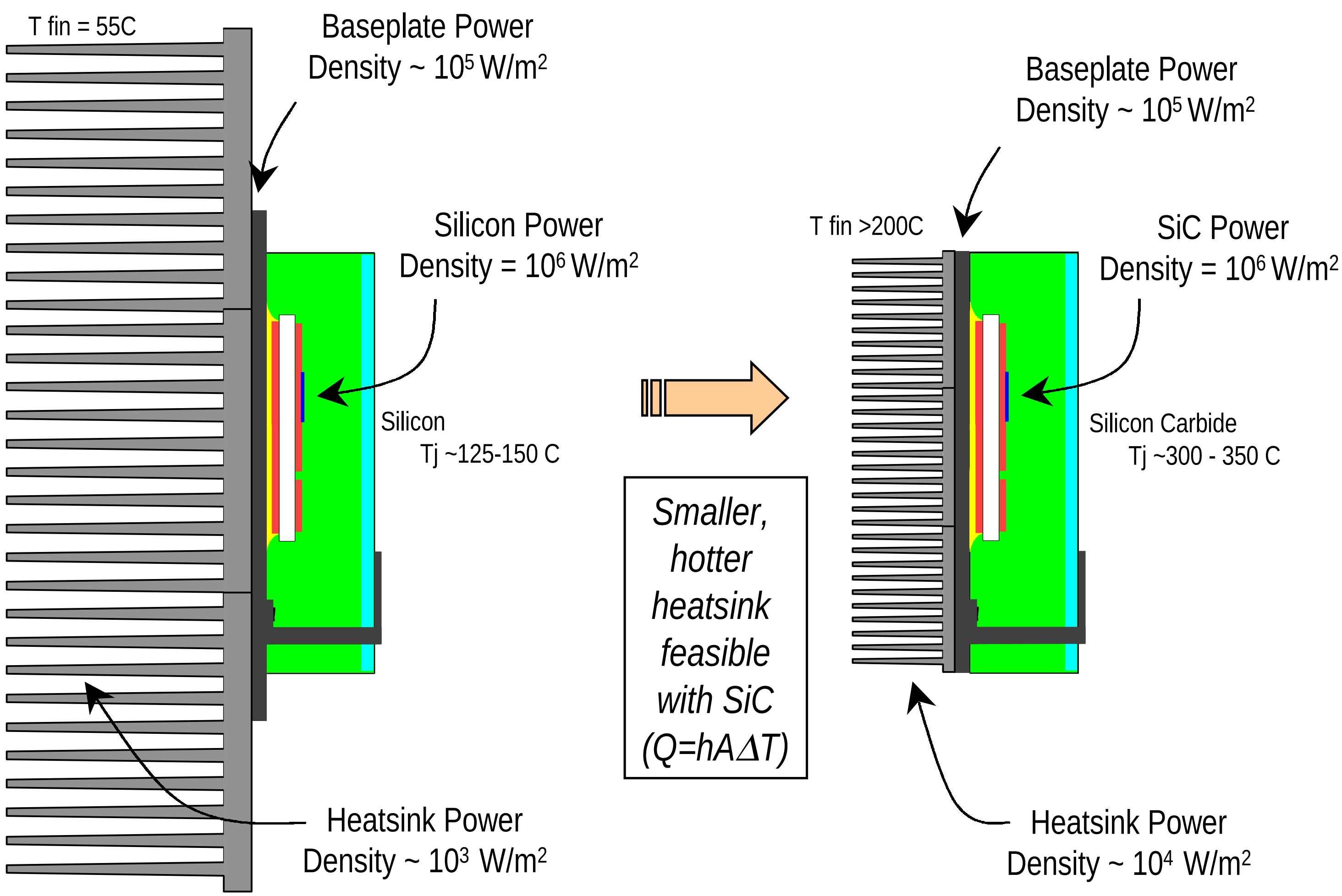
*Rockwell Science Center, Thousand Oaks, CA*

[1]*University of California, Santa Barbara CA*

**30 May, 2001**

Contract Number MDA97298C0002

# Decrease in System Volume Through Utilization Of *Silicon Carbide (SiC) Electronics*

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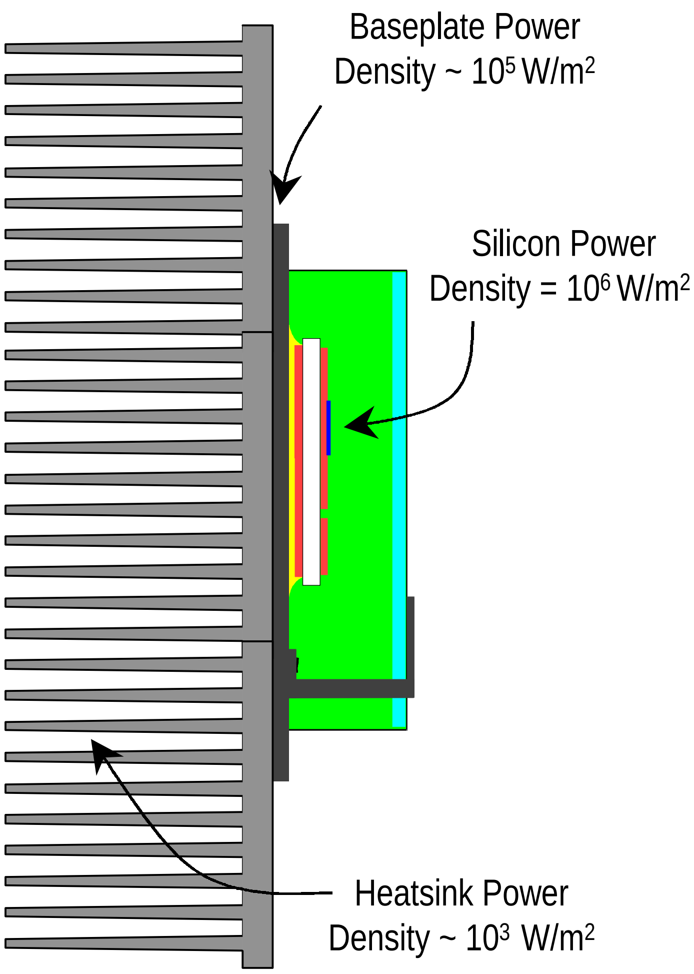
# Thermomechatronics

M.C. Shaw and E.R. Brown,[1]
*Rockwell Science Center, Thousand Oaks, CA*
*[1]University of California, Los Angeles CA*

## 30 May, 2001

Contract Number MDA97298C0002

# Thermal Management of Power Electronics: Spread Power Density from Device to Heatsink





5 hp Motor Drive Example

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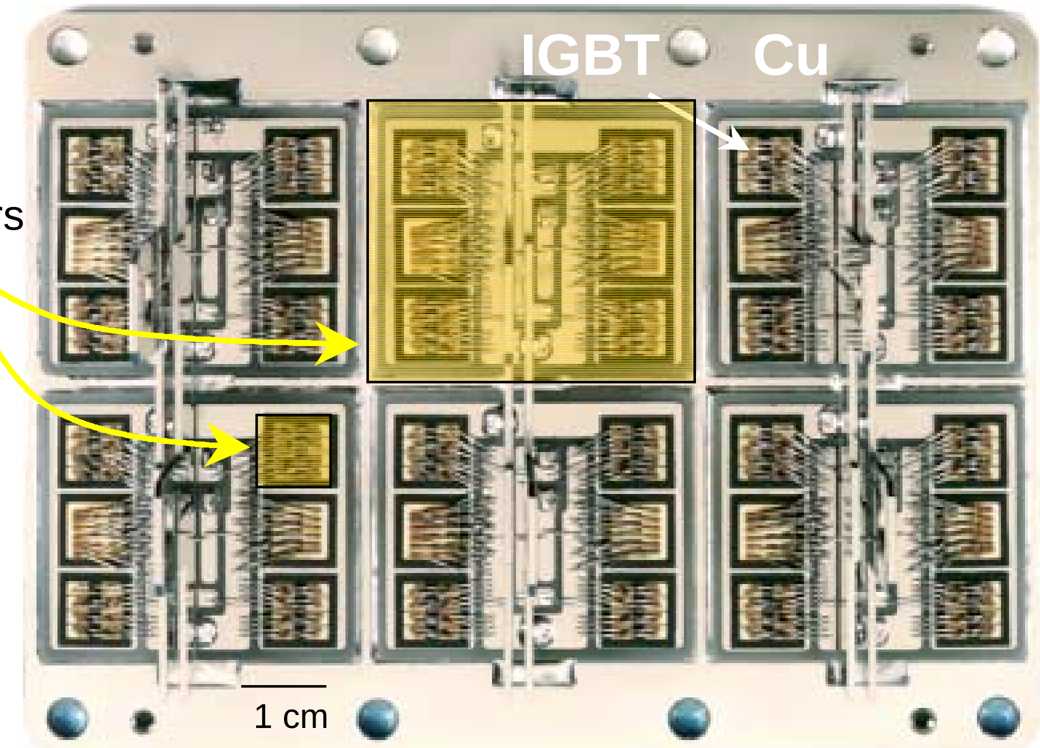
# Large Area Solder Joint Reliability in Power Assemblies

Examples of Buried Continuous Solder Layers




Internal view of a 1200A, 3300V IGBT module
(courtesy: Eupec GmbH+ Co.)

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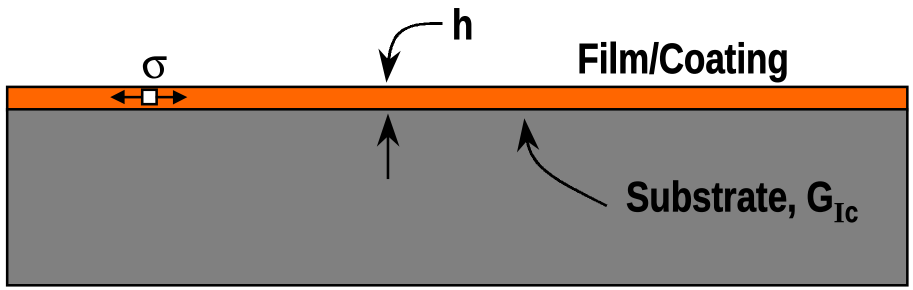
# Elastic Fracture Mechanics Energy Balance in Layered Systems




$\sigma$ = Stress in coating
h = Coating thickness
E, v = Elastic properties
Z ~ 0.3

$$\frac{Z\sigma^2 h\left(1-\upsilon^2\right)}{E} \quad \begin{matrix} > \\ < \end{matrix} \quad G_{Ic}$$

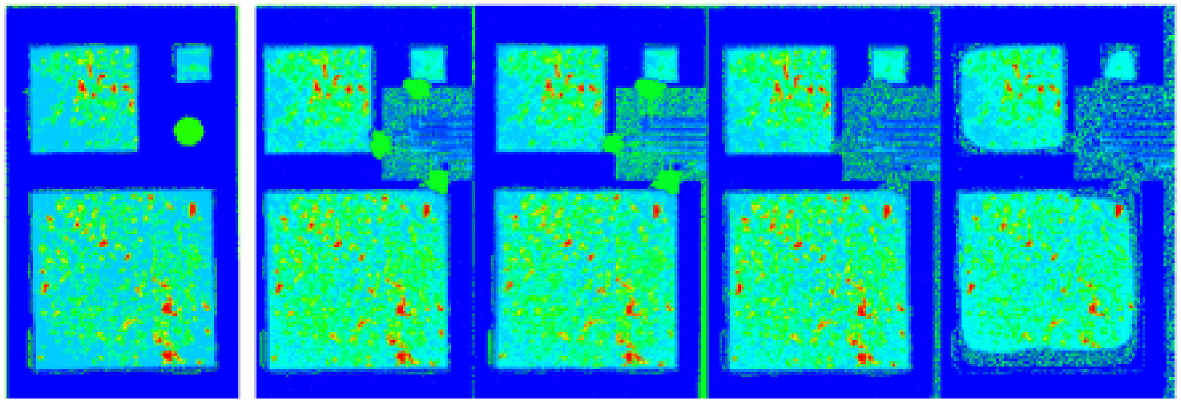
Driving Force for Crack Growth or Material or Interfacial Crack Growth Resistance

**Cracking depends on which is larger:**

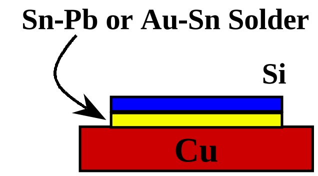
# Thermal Cycling of Sn - Pb (<u>Elastic/Plastic</u>) vs Au-Sn (<u>Elastic</u>) Joints

0.6"

**80Au20Sn on Copper**

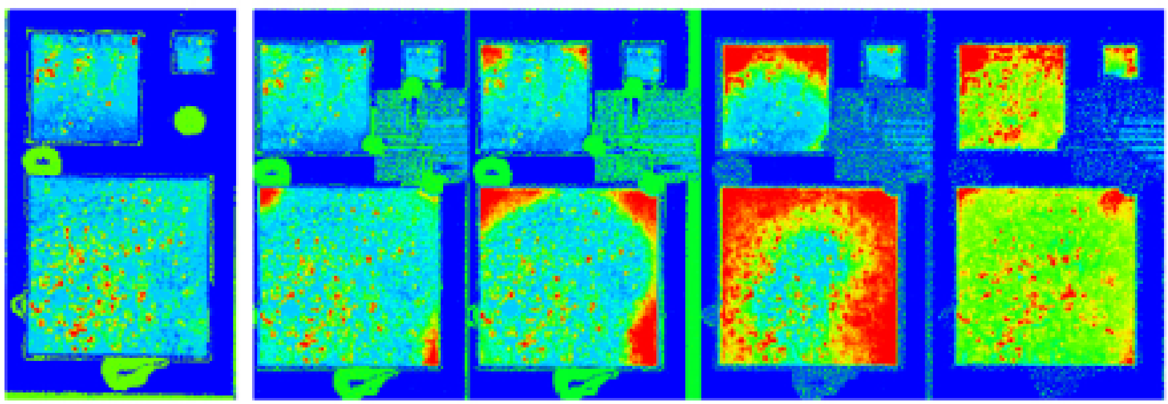


$\Delta\alpha$ = 14.1 ppm; Elastic Solder




As Soldered | 1 cycle | 10 cycles | 100 cycles | 1000 cycles

**63Sn37Pb on Copper**



$\Delta\alpha$ = 14.1 ppm, Elastic / Plastic Solder

*Ultrasonic Reflection Microscopy*

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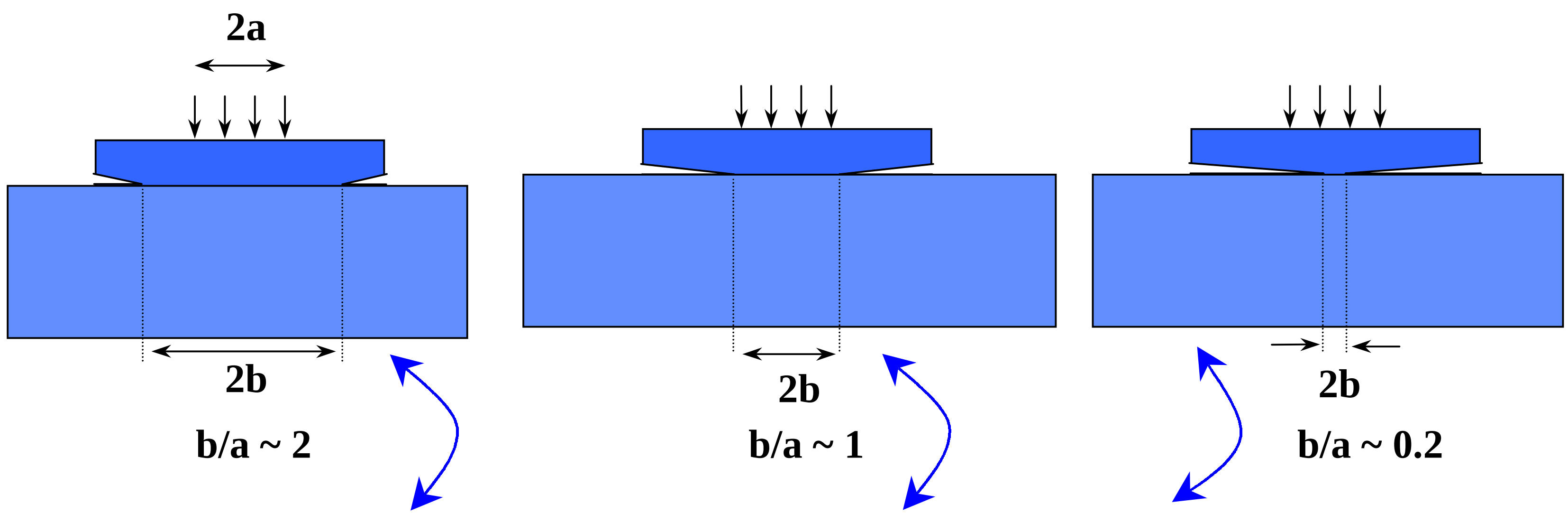
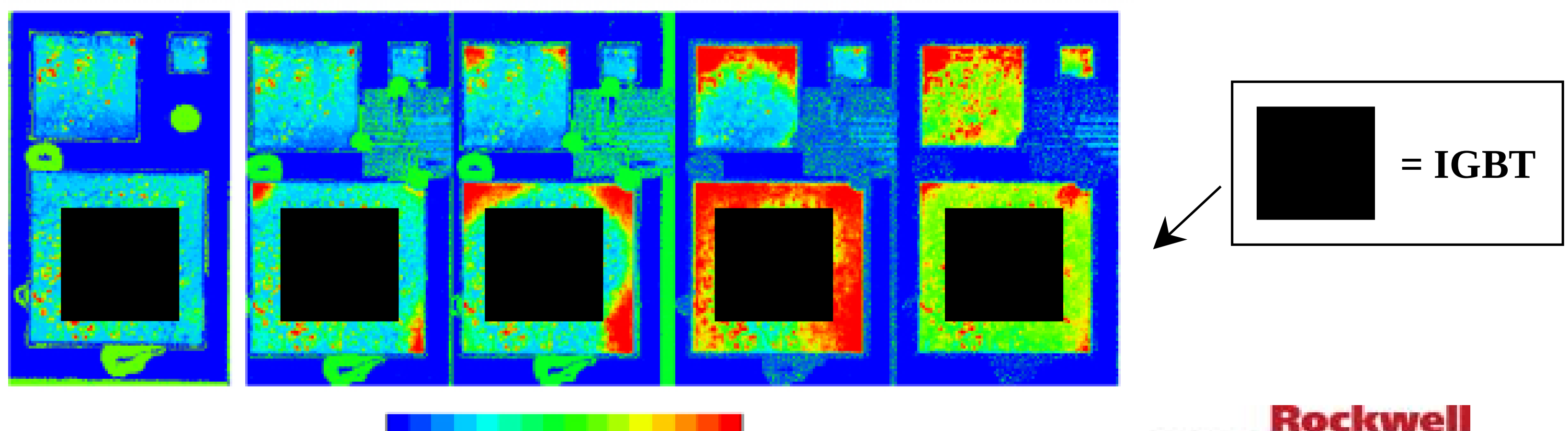
# Model of progressive crack growth in DBC/baseplate solder joint

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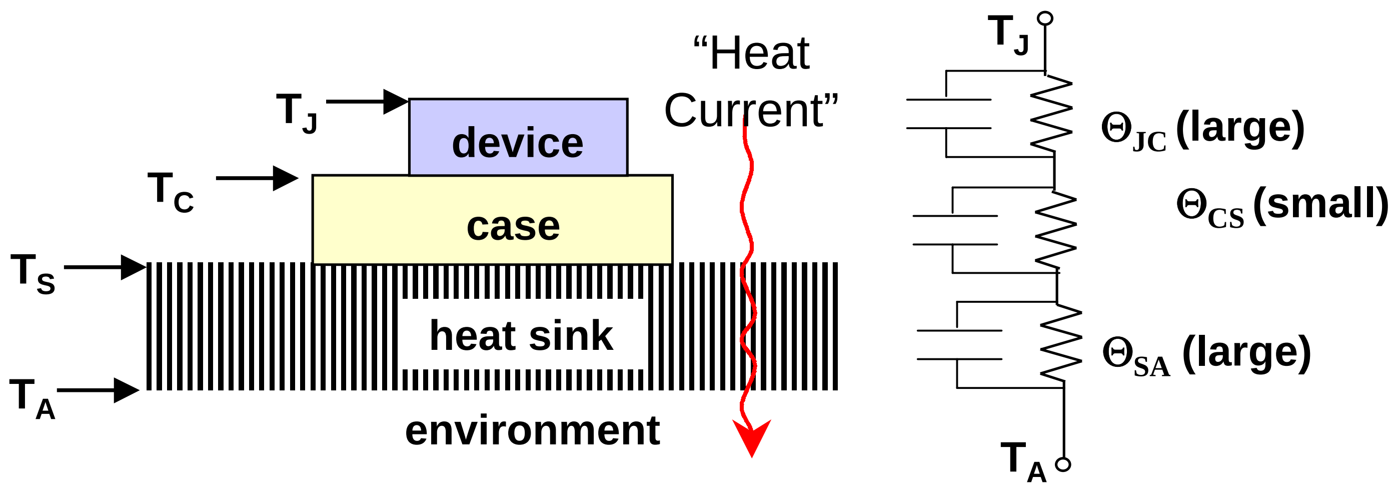
# Thermal Equivalent Circuit




$$\Theta_{JC} + \Theta_{CS} + \Theta_{SA} = \Theta_{JA} = (T_J - T_A)/P_0$$

| Thermal Resistance | Analytic Form | Typical Values |
|---|---|---|
| $\theta_{JC}$ | $\sim \rho t/A_s$<br>$\rho$ -> thermal resistivity, t -> thickness | $1.4^oC/W$ |
| $\theta_{CS}$ | $\sim \rho t/A_s$ | $\sim 0.1\text{-}1\ ^oC/W$ |
| $\theta_{SA}$ | $\sim 1/hA_s$<br>h -> heat transfer coefficient | $10\text{-}33^oC/W$ (natural convection);<br>$1\text{-}10^oC/W$ (forced air) |

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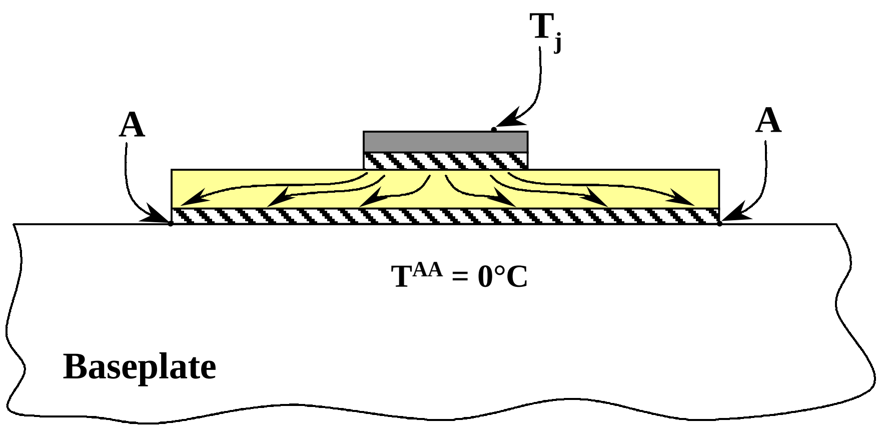
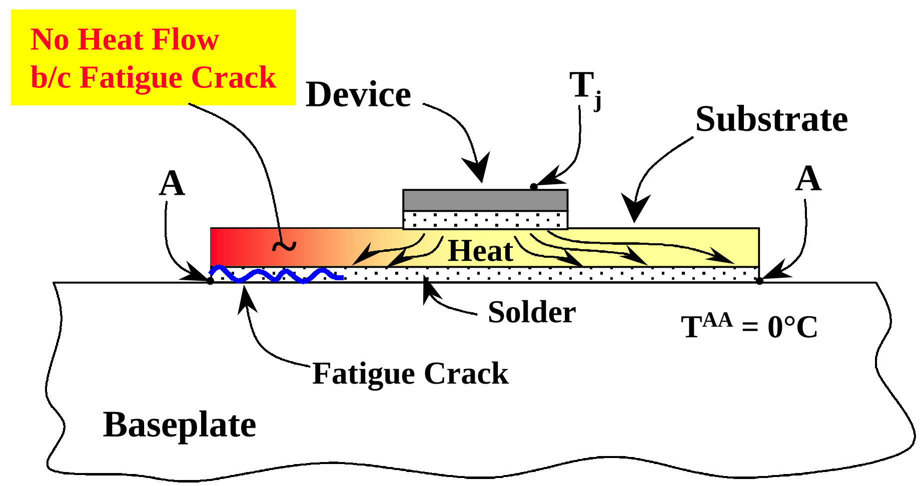
# Solder Joint Fatigue Raises Package Thermal Resistance




*Pristine condition - lowest thermal resistance*




*Thermally cycled condition - higher thermal resistance*

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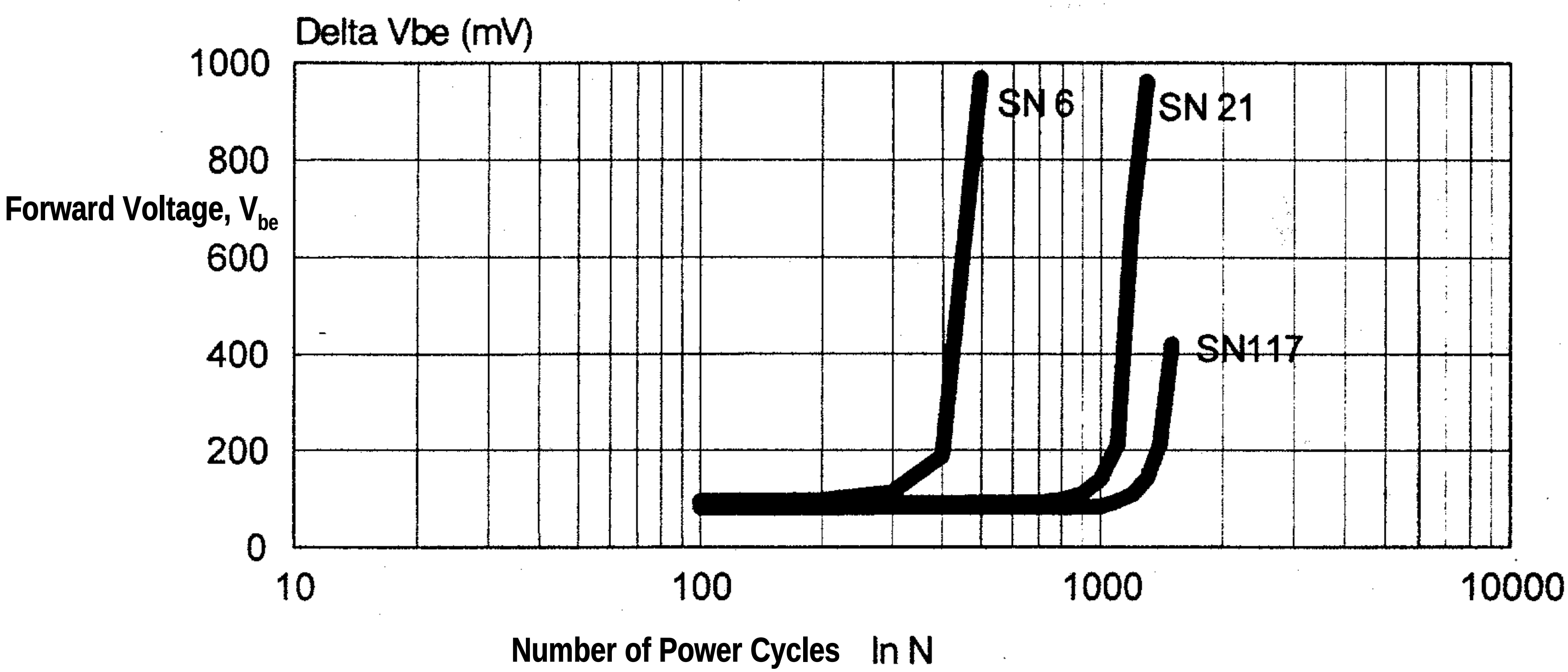
# Bipolar Transistor Performance Degradation with Repeated Power Cycling (Ref: Evans and Evans)

(Evans and Evans, IEEE Trans. Comp. Pack., Mfg. Tech., Part A, v. 21 no. 3 pp. 459 - 468, 1998)




***Experimental Results Showing Large Increase in Forward Voltage Drop, $\Delta V_{be}$, with Repeated Power Cycling, N***

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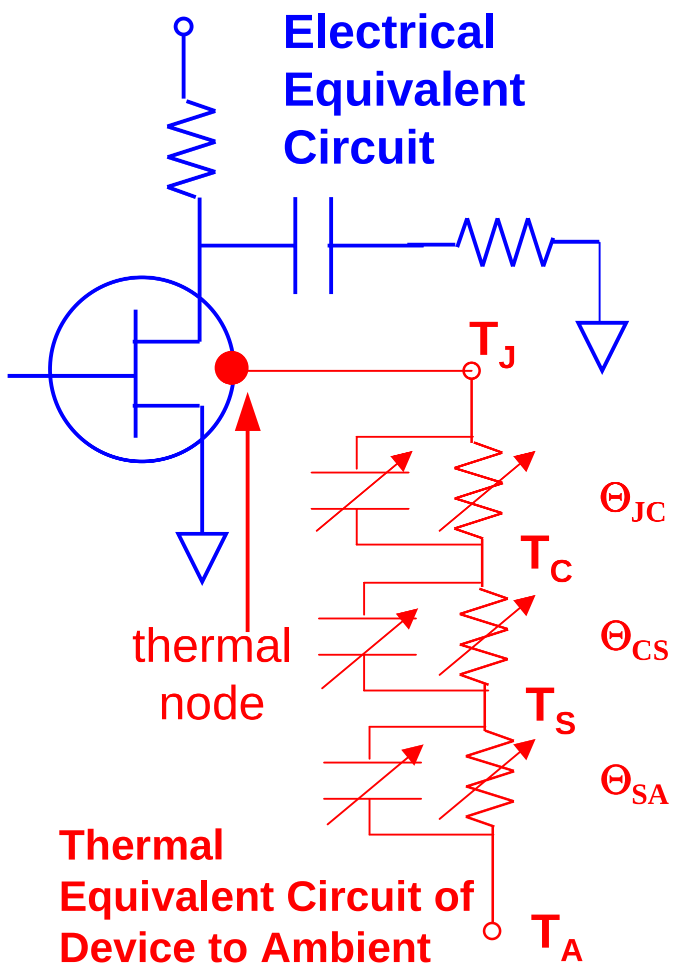
# Coupled Electro-Thermal Simulation




<u>**Modeling Features:**</u>

- **Nonlinear thermal circuit models**
- **Connect electrical to thermal circuits through unique "thermal node" (after A. Hefner of NIST)**
- **SPICE-like environment**

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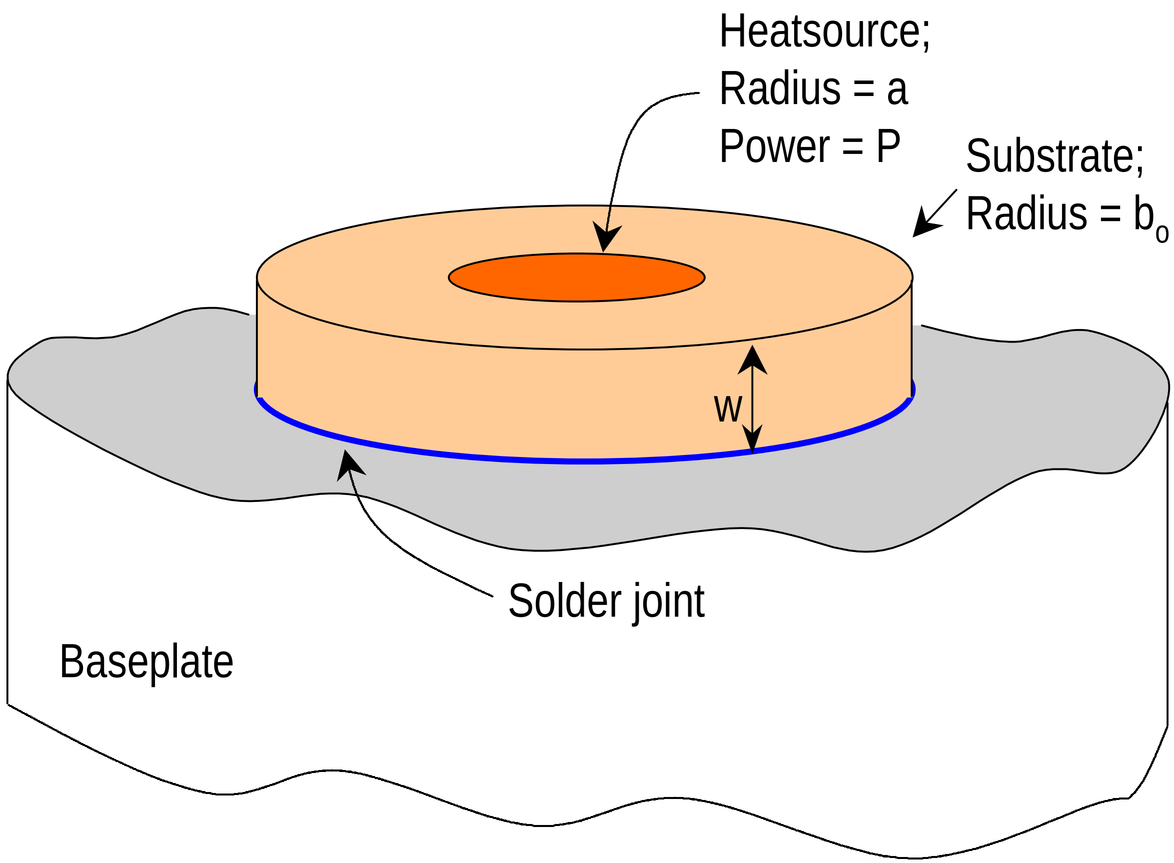
# Schematic of Model Package Geometry

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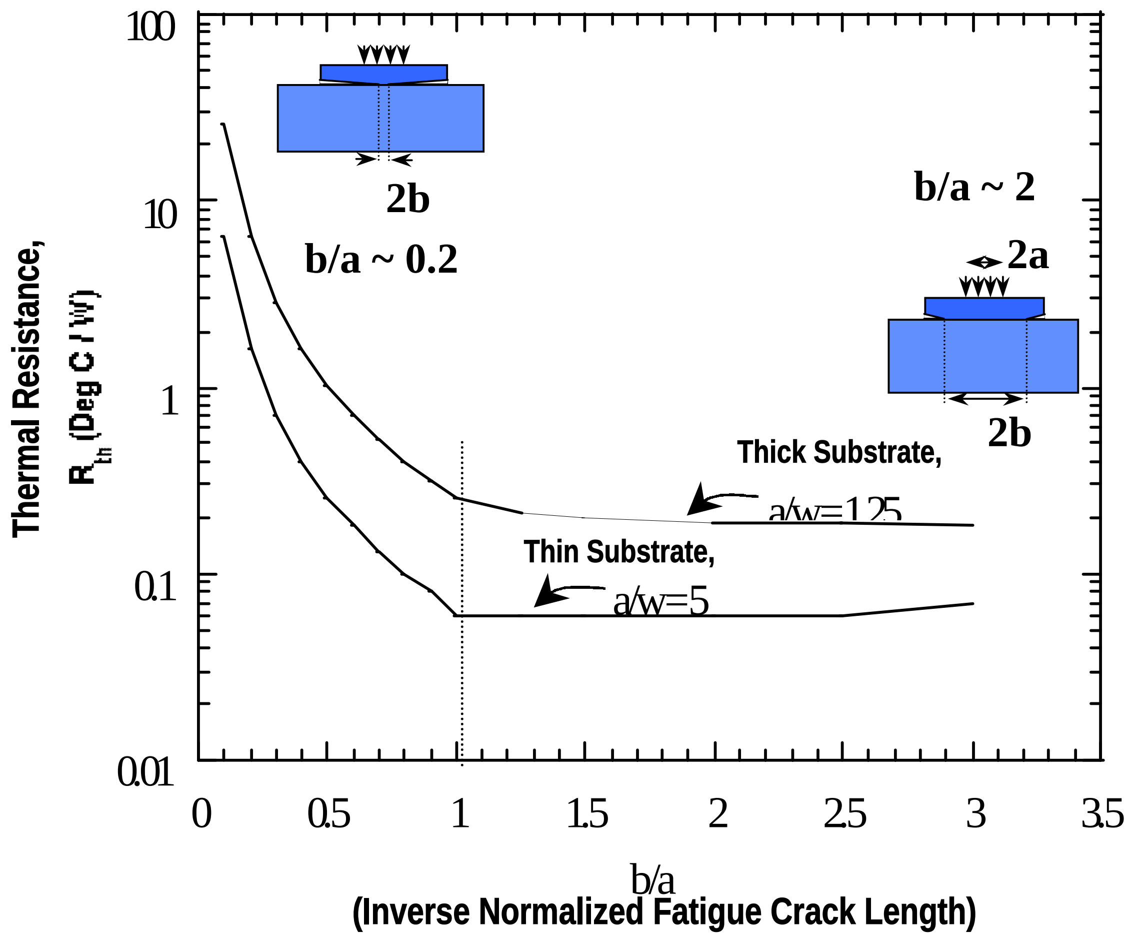
# Calculated Thermal Resistance, $R_{th}$, vs. Inverse Normalized Fatigue Crack Length, b/a.

*Note the rapid increase in $R_{th}$ with penetration of the fatigue crack into the region below the device (b/a~1)*

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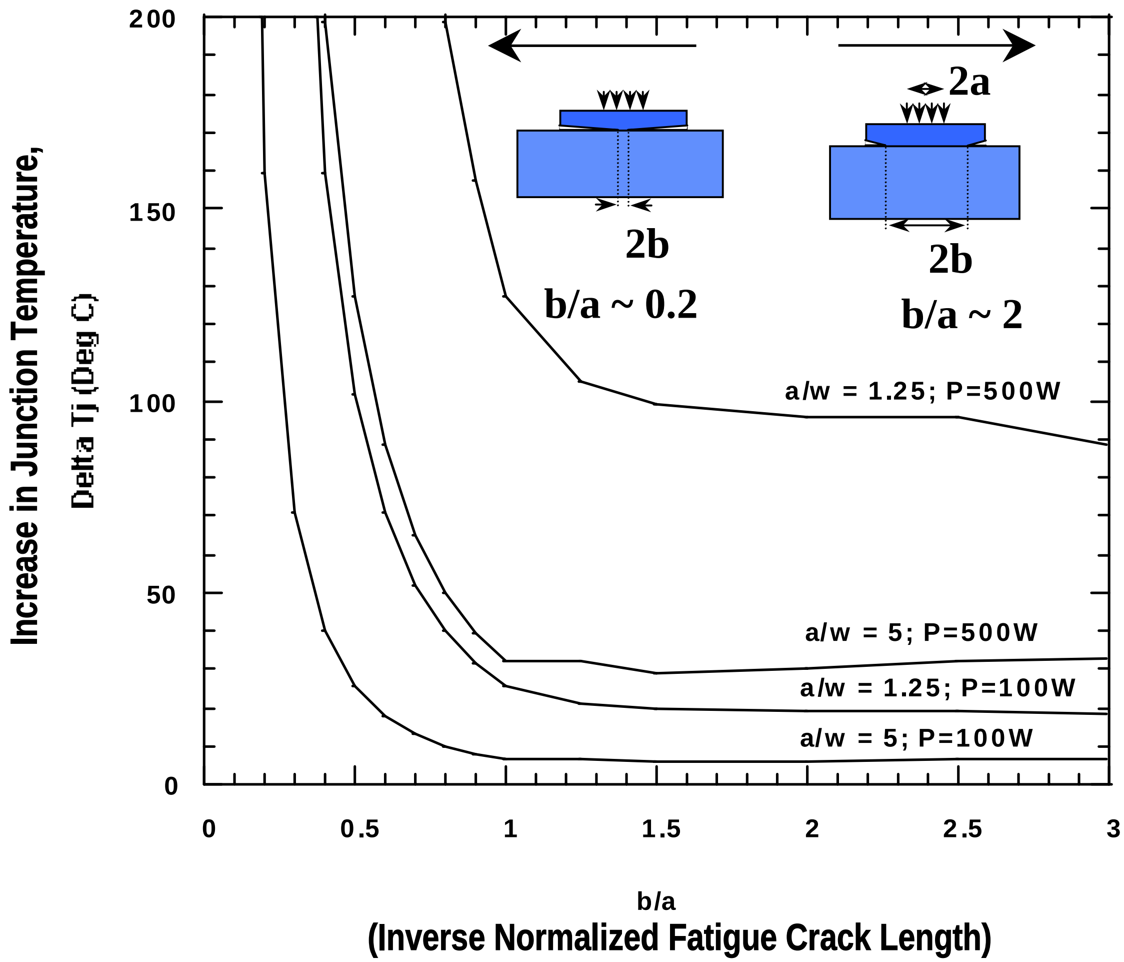
# Dependence of Junction Temperature Increase, $\Delta T_j$, on Inverse Normalized Fatigue Crack Length, b/a




*Two different power levels and substrate thicknesses.*

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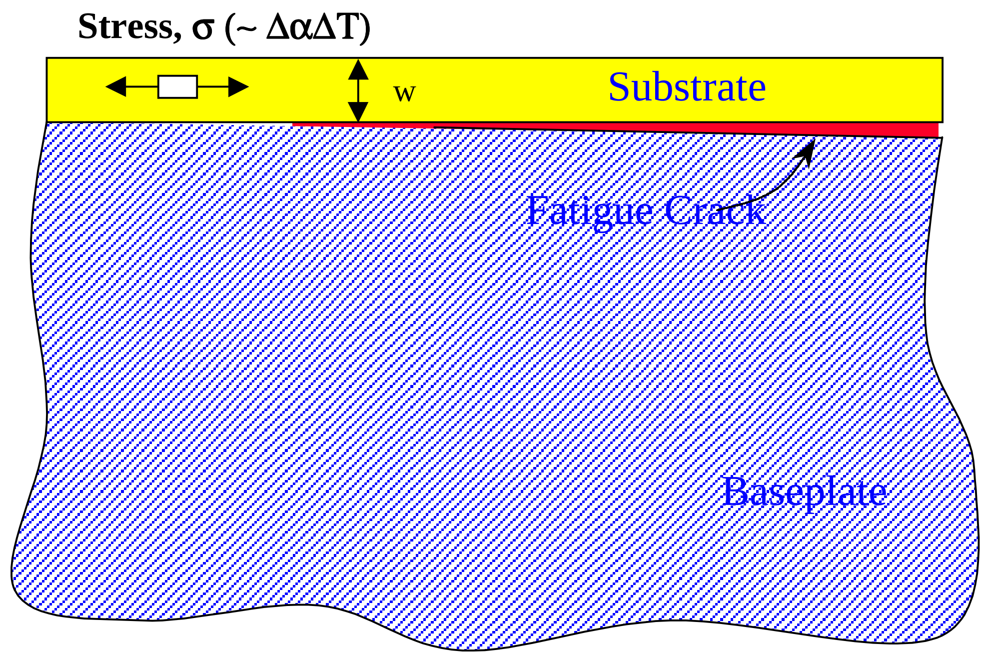
# Strain Energy Release Rate, $G_{Ic}$, Depends on $\Delta T_j$

$$\frac{Z\sigma^2 h\left(1-\upsilon^2\right)}{E} = G_{Ic}$$




*Strain energy release rate is the driving force for fatigue crack growth*

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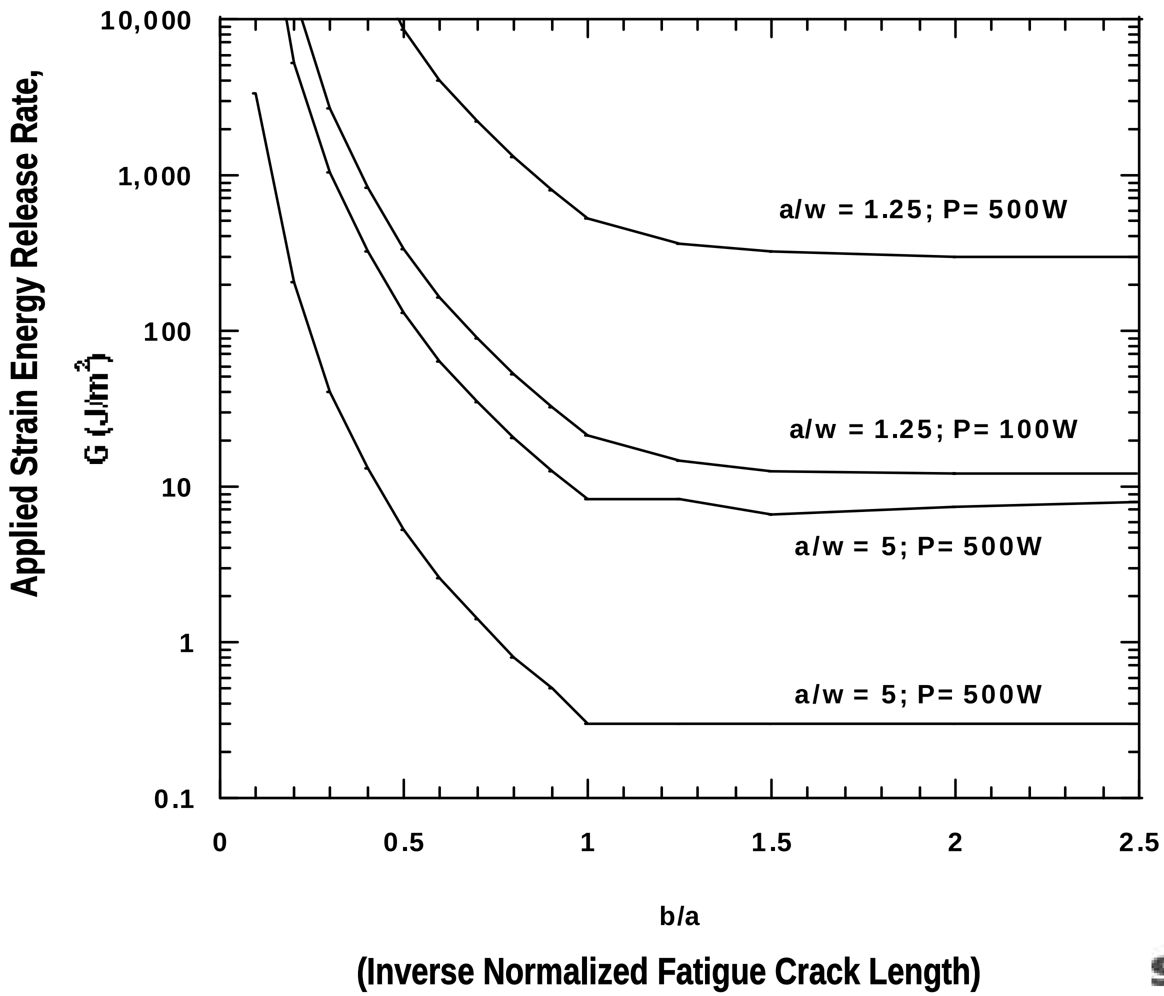
# Applied Strain Energy Release Rate, G, at Fixed Device Power Dissipation vs. b/a.

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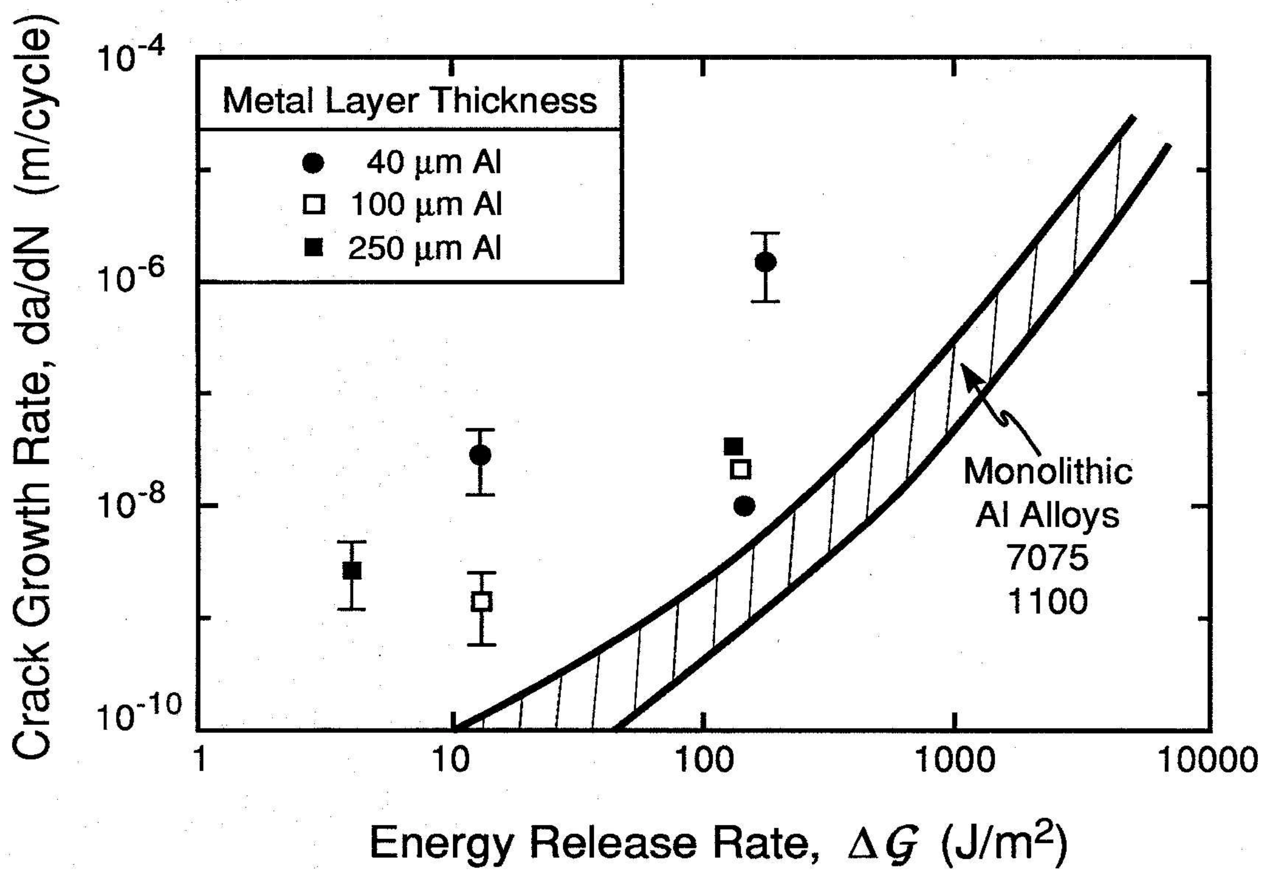
## Experimental crack growth ***rate*** data, da/dN, vs. cyclic ***strain energy release rate range*** $\Delta G$ for the Al-$Al_2O_3$ and Al-Al systems.

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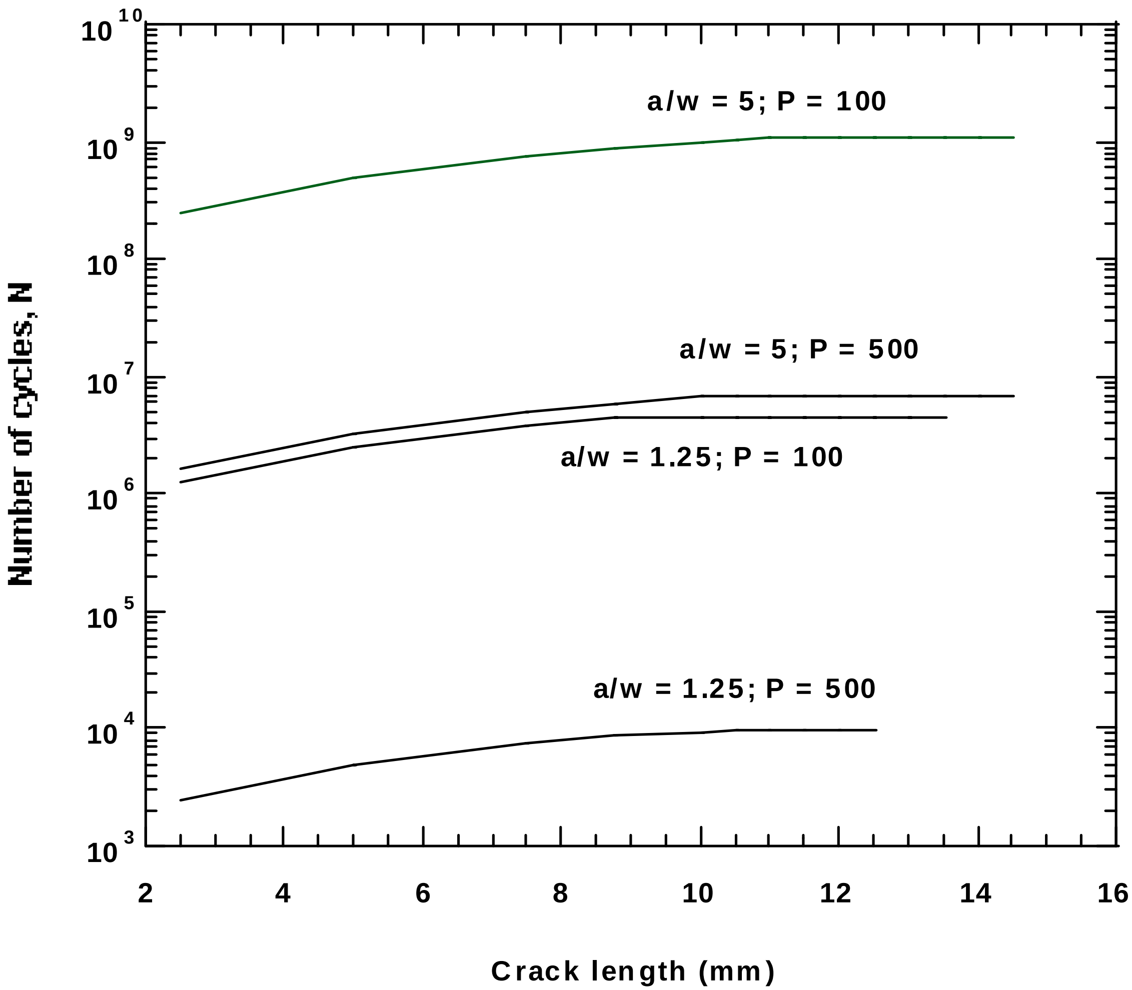
# Relationship between the number of power cycles, N, and the crack length, l for two different power levels and substrate thicknesses.




*Note the highly nonlinear relationship between the crack lengths and number of power cycles.*

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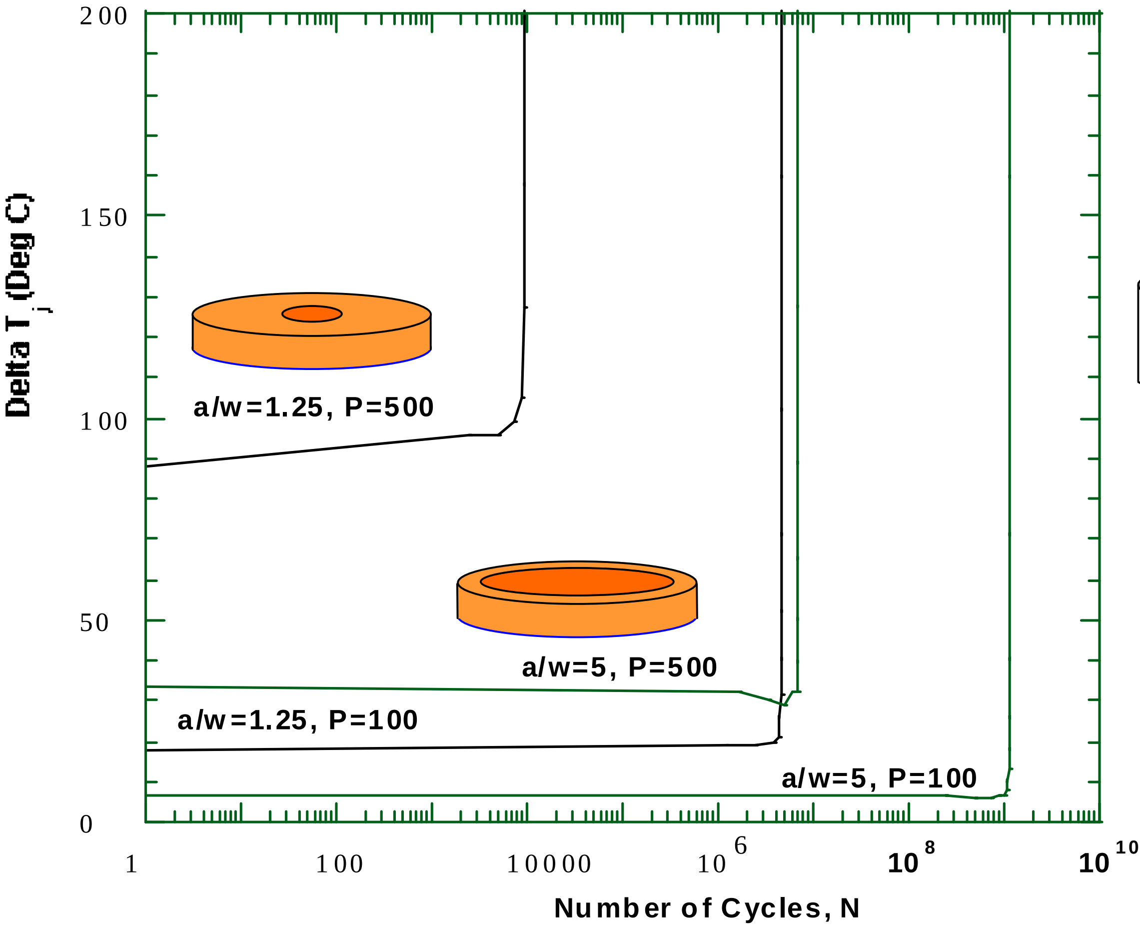
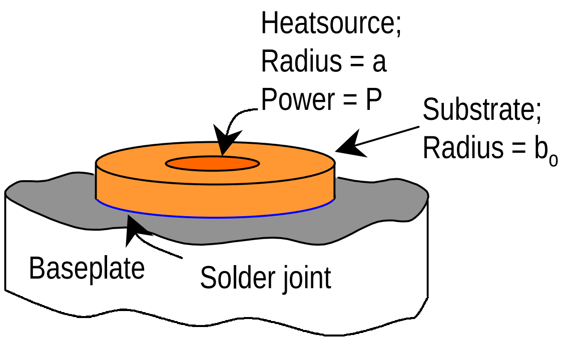
# Predicted Junction Temperature Increase, $\Delta T_j$, vs. Power Cycles, N

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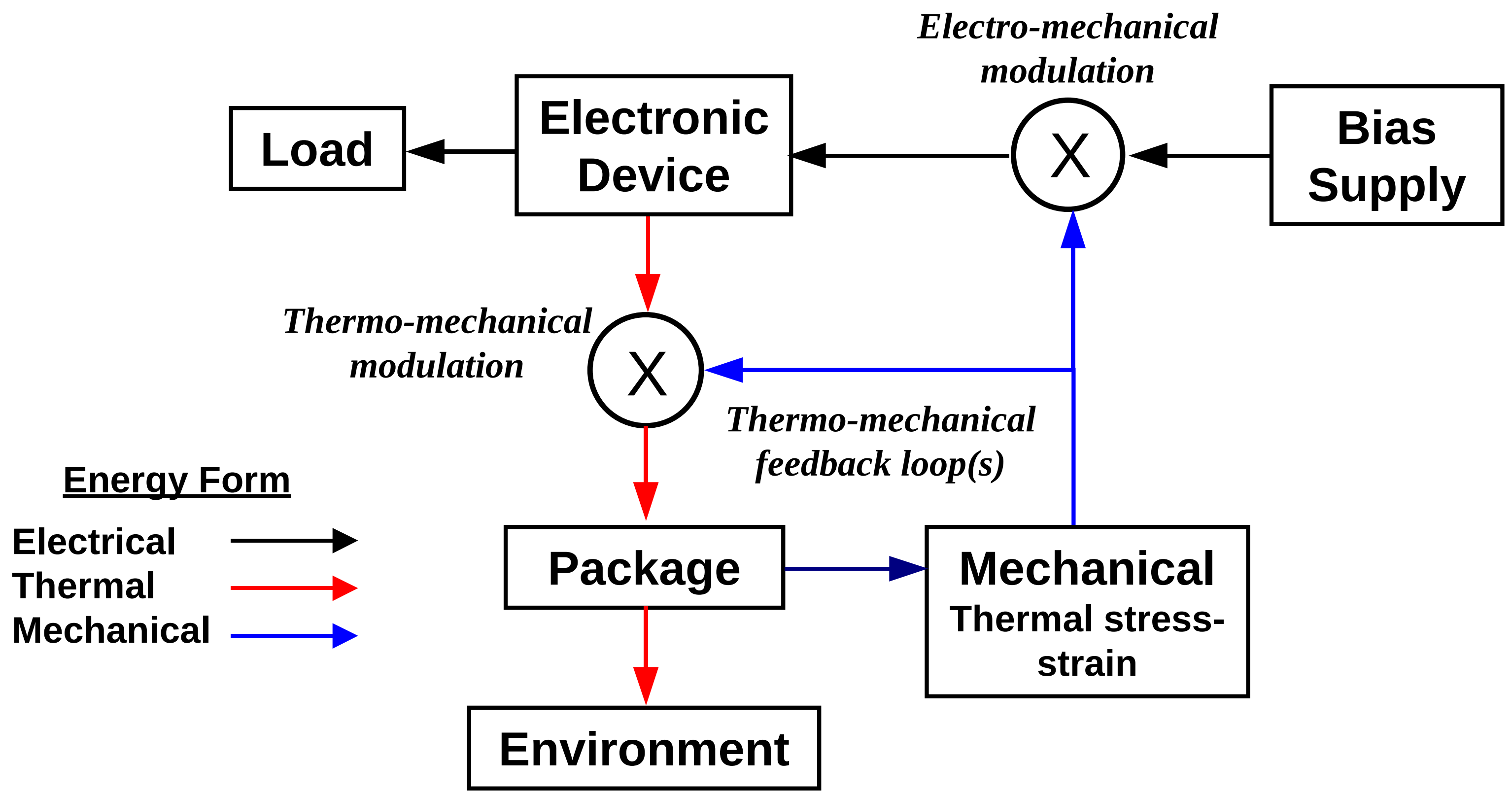
# *Thermomechatronic* Analysis of coupled flow of electrical, thermal and mechanical energy

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# Conclusions

• **Advantages of new approaches <u>must be demonstrated at the system, e.g., motor drive, level</u>.**

**_Device_ Power Density (A/cm$^2$ or W/cm$^2$ )**
**_System_ Power Density (W/m$^3$)**
**Lifetime Assurance of Entire System**
**System Cost Analysis Ultimately Required**

•**Research Needs:**

**<u>1) Materials</u>**

- **Controllable and High Thermal Conductivity**
- **Functional Integration of Electrical, Thermal, Mechanical Features**
- **High Temperature Capability**
- **Lightweight**
- **Compatible with Solid-State Devices**
- **Easily Processed**

**<u>2) Efficient, System-Based Design Methodologies</u>**

- **Mechanical, Thermal, Coupling**
- **Lifetime Prediction / Reliability**
- **Design Optimization / Tradeoff Capability**

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